# Session V. Doppler Related Research

Vertical Wind Estimation from Horizontal Wind Measurements

Dan Vicroy, NASA Langley Research Center

NASA LaRC

# Vertical Wind Estimation From Horizontal Wind Measurements

**Dan D. Vicroy**

Flight Management Division
Vehicle Operations Research Branch

NASA/FAA Wind Shear Review Meeting

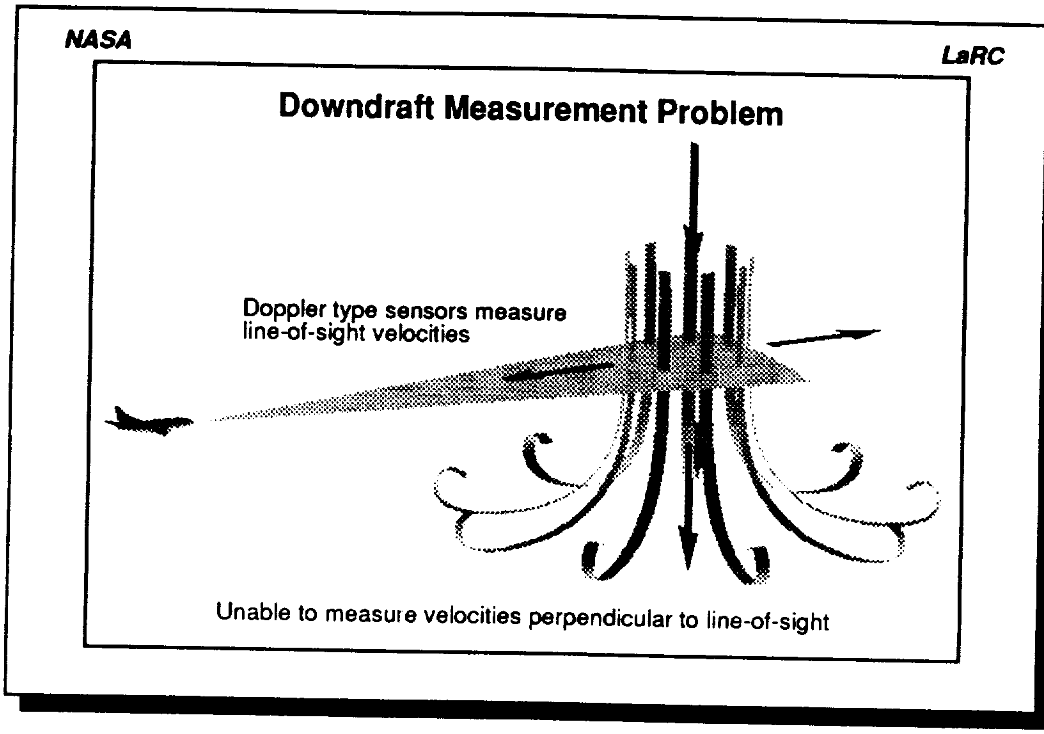
April 14-16, 1992

NASA LaRC

## Outline

- The Downdraft Measurement Problem
- Initial Research Activities & Results
- Current Methodologies
- Summary and Future Activities

This presentation will begin with a brief description of the downdraft measurement problem for airborne Doppler based systems and the importance of the downdraft in assessing the hazard posed by a microburst wind shear. This will be followed by a review of research on the feasibility of using simple microburst models to compute the downdraft from horizontal wind measurements. The current methodologies for computing the vertical wind will then be discussed. A summary of the results and the plan for future research will conclude the presentation.




Two of the airborne forward-look sensor technologies being tested to provide advanced warning of wind shear are Doppler RADAR and LIDAR. Both measure the Doppler shift of reflected light or radio waves from the aerosols, rain drops and other debris in the air, to determine the line-of-sight relative velocity of the air. An inherent limitation of this type of system is its inability to measure velocities perpendicular to the line-of-sight. The presence of a microburst can be detected by measuring the divergence of the horizontal velocity profile, yet, the inability to measure the downdraft can result in a significant underestimate of the magnitude and spatial extent of the hazard.

NASA LaRC

## Wind Shear Hazard Index

*The "F-factor"*

**For straight and level flight**

$$F = \frac{\dot{u}}{g} - \frac{w}{V}$$

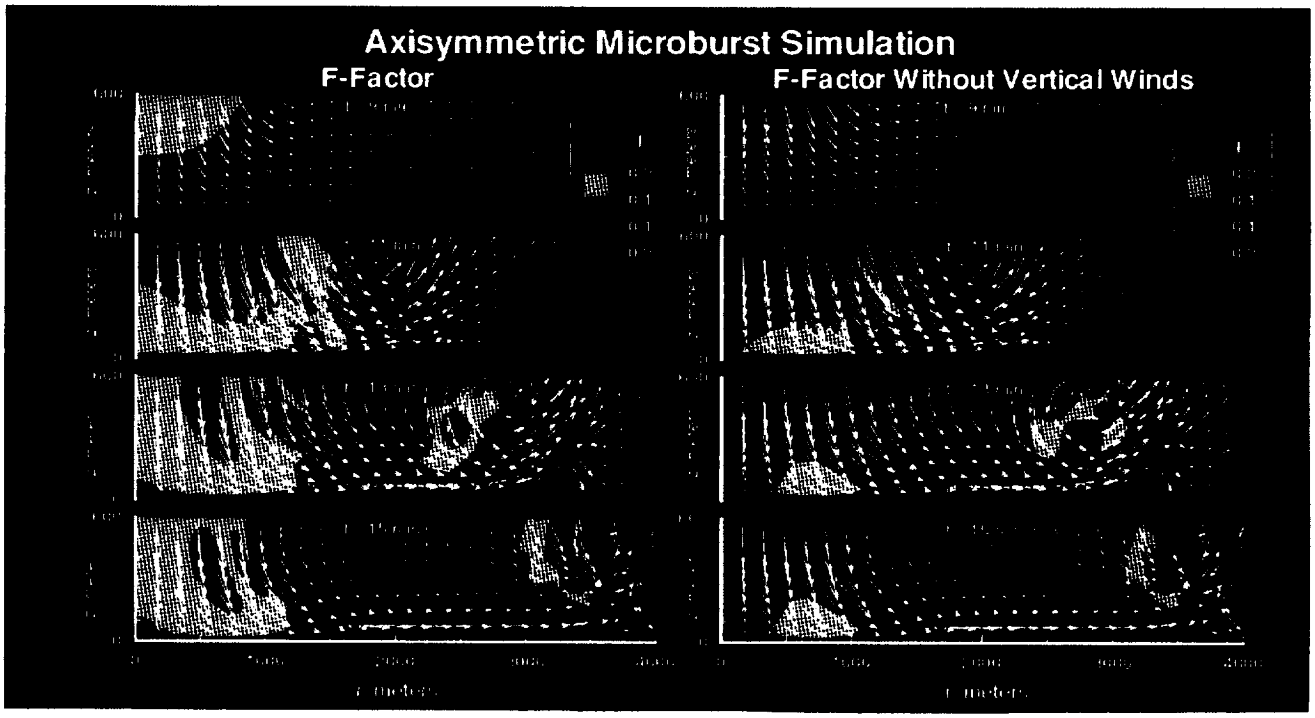
**Related to the potential rate of climb**

$$\dot{h}_p = V\left(\frac{T - D}{W} - F\right)$$

The magnitude of the hazard posed by a microburst to an airplane can be expressed in terms of the "F-factor"†. The F-factor is a nondimensional hazard index that is directly related to the potential rate of climb capability of the airplane in wind shear. For straight and level flight the F-factor is a simple function of the rate of change of the horizontal wind ($\dot{u}$), the vertical wind (w), the acceleration due gravity (g), and the airplane's airspeed (V). Positive values of F indicate a performance-decreasing situation, and conversely, negative values indicate a performance-increasing condition.

† Bowles, Roland L.: *Reducing wind shear Risk Through Airborne Systems Technology.* 17th Congress of the International Congress of Aeronautical Sciences, Stockholm, Sweden, September 1990.

ORIGINAL PAGE
COLOR PHOTOGRAPH




This chart shows F-factor contour plots and the wind velocity vectors for an axisymmetric microburst at four stages in its life cycle. This microburst was generated with the Terminal Area Simulation System (TASS) high-fidelity atmospheric model.† The F-factor contours were computed for an airplane flying level at 130 knots. The contours on the left include the vertical wind in the F-factor calculation while the contours on the right do not. The contours on the right represent the detectable hazard from solely horizontal wind measurements. The magnitude and spatial extent of the detectable hazard is clearly diminished. This chart illustrates the need for some means of estimating the magnitude of the vertical winds from the horizontal wind measurements.

† Proctor, F. H.: *The Terminal Area Simulation System. Volume I: Theoretical Formulation.* NASA CR-4046, April 1987.

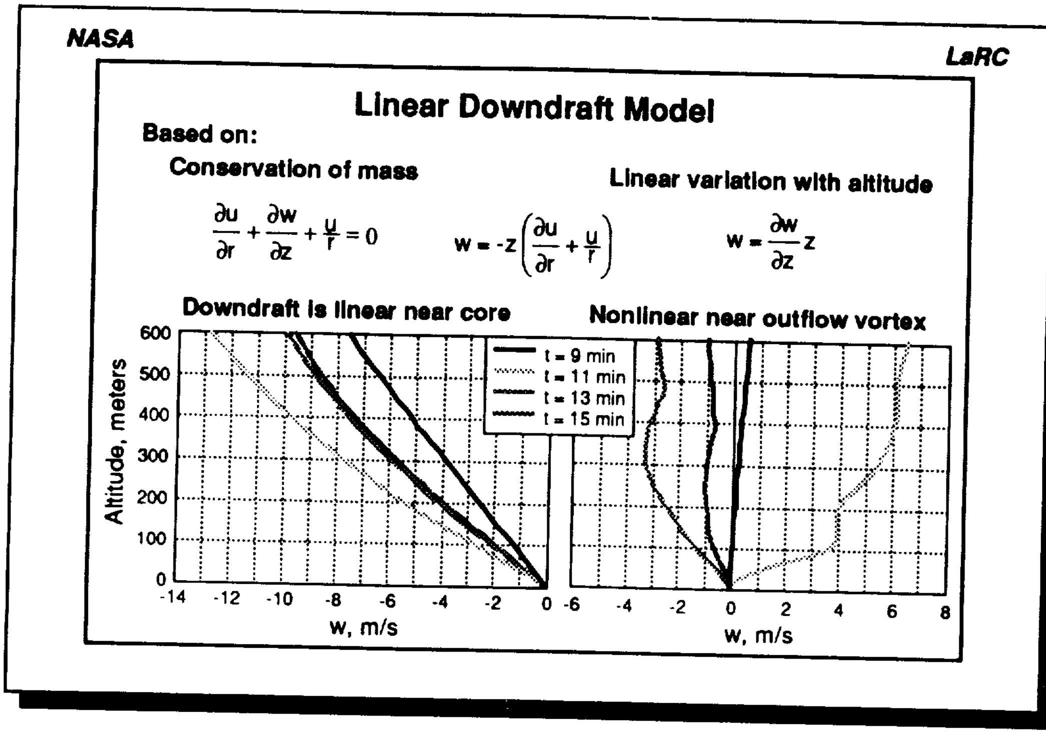
p. 396

NASA LaRC

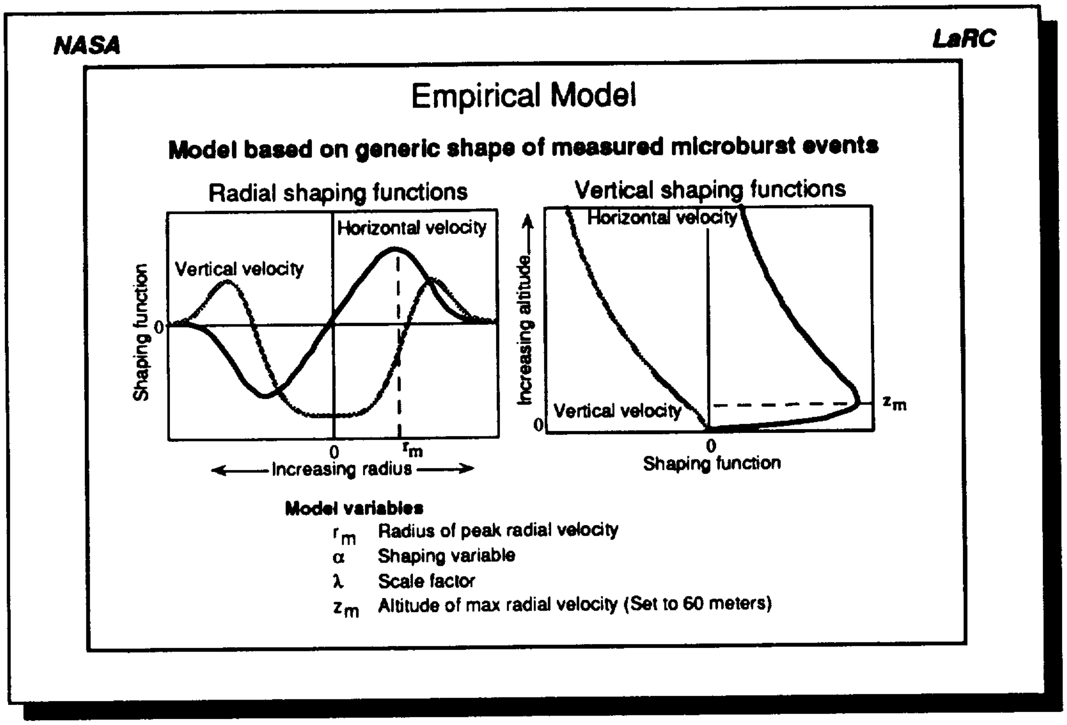
## Initial Research Activities

- Focused on downdrafts in microbursts
- Tried three microburst downdraft models of varying complexity
  - Linear model
  - Empirical model
  - Ring Vortex model

The initial research objective was to determine the feasibility of computing the downdraft of a microburst from horizontal wind measurements using simple microburst models. No attempt was made to compute updrafts or vertical winds from other weather phenomena, such as gust fronts, since these were considered performance increasing and thus were not hazardous. Three microburst downdraft models were tested. The three models represented varying degrees of complexity. The linear model was the simplest and the ring vortex model was the most complex.




The "linear model" is the simplest of the three models tested. It is based primarily on the principle of conservation of mass, which is expressed on this chart in cylindrical coordinates. If the vertical wind is assumed to be zero at the ground and vary linearly with altitude, then the vertical wind can be expressed as a simple function of the radial velocity profile. The linear assumption appears reasonable in or near the core of the microburst but poor near the outflow vortex.



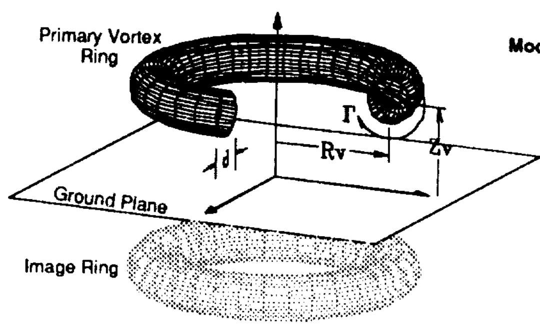

As the name implies, this model is based on measurements of several microburst events. The empirical model is an axisymmetric, steady-state model that uses shaping functions to satisfy the mass continuity equation and simulate boundary layer effects†. The shaping functions are used to approximate the characteristic profile of the microburst winds. The empirical model is fully defined through four model variables: the radius and altitude of the maximum horizontal wind, a shaping variable, and a scale factor.

† Vicroy, Dan D.: *A Simple, Analytical, Axisymmetric Microburst Model for Downdraft Estimation.* NASA TM-104053, DOT/FAA/RD-91/10, February 1991.

*NASA* *LaRC*

## Ring-Vortex Model

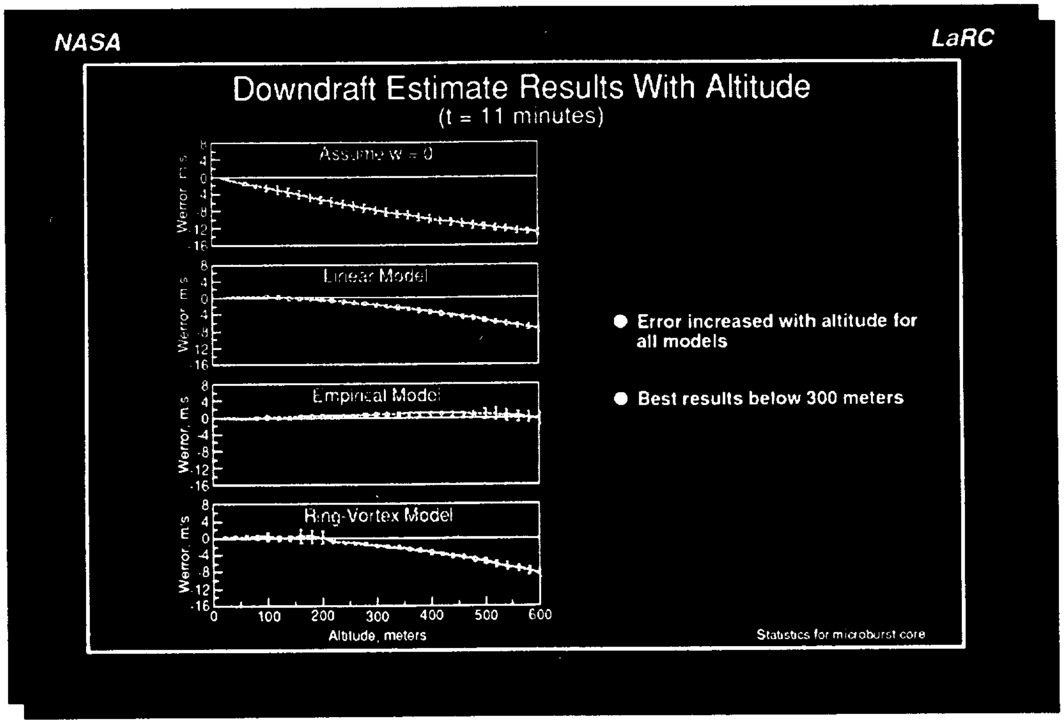
**Model based on theoretical simulation of microburst flow characteristics**



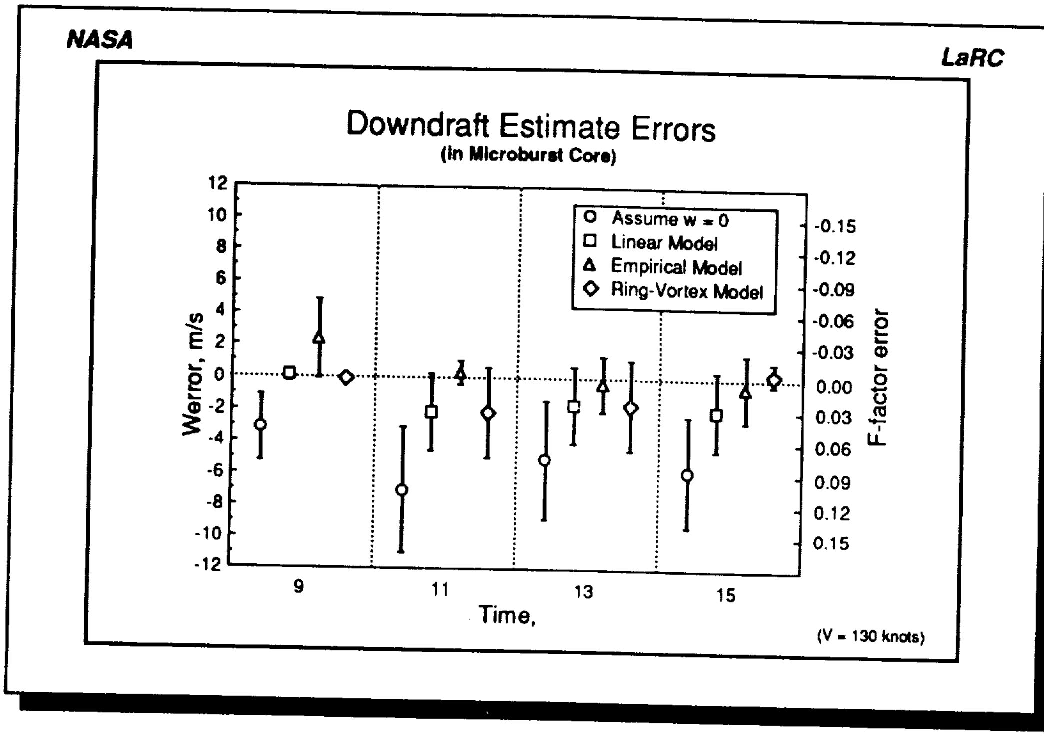

**Model variables**

- Rv Radius of vortex ring
- Zv Altitude of vortex ring
- d Diameter of ring core
- Γ Vortex strength

The ring-vortex model is a theoretically derived model based on the assumption that the flow field generated by a vortex ring near a flat plate is similar to that of a microburst. This model has a primary vortex ring located above the ground and a mirror image ring located equidistant below the ground plane. The mirror image ring is used to satisfy the no-flow through the ground boundary condition. The vortex ring model is defined by four model variables: the radius and altitude of the primary vortex ring, the diameter of the viscous core, and the circulation strength.




An example of the mean and standard deviation of the downdraft estimate errors from the three models is shown here for the TASS axisymmetric microburst presented earlier. The errors are shown for each altitude at which a downdraft profile was estimated. Also shown is the error that results from assuming no downdraft (w=0). The errors were computed in the downdraft region of the microburst as the actual minus the estimated value. The errors increased with altitude for all of the models and all worked well below 300 meters. The empirical model worked particularly well in this example but had less favorable results in other test cases.




The total mean and standard deviation of the downdraft error over the full altitude range (0 to 600 meters), is shown here for each of the four stages of the microburst. Also shown in the figure is the corresponding F-factor error for an airspeed of 130 knots. None of the models had significantly better performance than the others. The linear model worked well for all the cases at altitudes below 200 meters. The empirical model produced the best results for the 11 and 13 minute cases. The 11 minute case is near the time of maximum shear and is perhaps the most critical from a hazard perspective.

NASA LaRC

## Initial Research Results

- Downdraft estimation errors increased with altitude
- No significant improvement with increased model complexity
- Model fitting technique requires knowledge and tracking of divergence center

The primary result of this initial study was to establish that simple microburst models could be used to estimate the downdraft from horizontal wind measurements. For the three models tested the downdraft estimate errors increased with altitude and there was no significant improvement with model complexity. One difficulty of the model based downdraft estimation technique is the requirement that the model be referenced about the divergence center of the microburst. This requirement poses system implementation issues such as identification and tracking of the divergence center, which were not addressed in this study. Details of this initial study can be found in AIAA paper 91-2947 "Assessment of Microburst Models for Downdraft Estimation" by Dan D. Vicroy.

NASA

LaRC

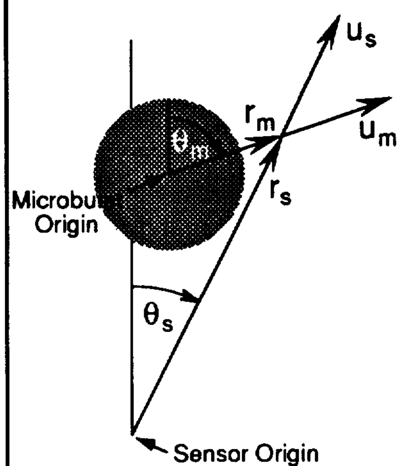
## Current Research Efforts

- Transformation of radial shear from microburst to sensor referenced coordinate system
- Development of new vertical wind estimation techniques
- Application of new techniques to '91 flight test data

The new wind shear hazard criterion, which was introduced by Mike Lewis (NASA LaRC) in an earlier presentation, defines the hazard as the F-factor averaged over one kilometer. Since the F-factor is now being averaged, the updrafts as well as the downdrafts must be computed. This required a restructuring of the techniques discussed earlier. This was accomplished by first translating the microburst-referenced wind field to a sensor referenced coordinate system. Simplifications were made to this transformation which manifested new vertical wind estimation techniques from Doppler sensor measured winds. These techniques were then tested using measured winds from the '91 flight tests to determine their viability.

NASA LaRC

## Radial Shear Transformation Equation
(In Microburst Core)




Assuming a symmetrical microburst with no rotational velocity

$$\frac{\partial u_s}{\partial r_s} = \frac{\partial u_m}{\partial r_m} \cos^2(\theta_m - \theta_s) + \frac{u_m}{r_m} \sin^2(\theta_m - \theta_s)$$

In the core of a microburst:

$$\frac{\partial u_m}{\partial r_m} \approx \frac{u_m}{r_m}$$

therefore:

$$\frac{\partial u_s}{\partial r_s} \approx \frac{\partial u_m}{\partial r_m} \approx \frac{u_m}{r_m}$$

or:

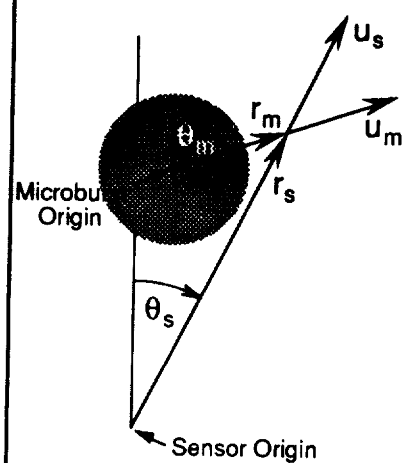
$$\frac{\partial u_m}{\partial r_m} + \frac{u_m}{r_m} = -\frac{\partial w}{\partial z} \approx 2\,\frac{\partial u_s}{\partial r_s}$$

This chart shows the radial shear transformation equation from a microburst-centered coordinate system to a sensor-referenced coordinate system under some simplifying assumptions. If the radial shear is assumed to be linear in the microburst core, then the transformation equation becomes a simple equality. If this equality is then applied to the mass conservation equation, a simple equation for the vertical velocity gradient as a function of the sensor measured radial shear is obtained.

NASA LaRC

## Radial Shear Transformation Equation

(Outside Microburst Core)




Assuming a symmetrical microburst with no rotational velocity

$$\frac{\partial u_s}{\partial r_s} = \frac{\partial u_m}{\partial r_m} \cos^2(\theta_m - \theta_s) + \frac{u_m}{r_m} \sin^2(\theta_m - \theta_s)$$

Outside microburst core:

$$\frac{u_m}{r_m} \rightarrow 0 \text{ as } r_m \rightarrow \infty$$

therefore: $$\frac{\partial u_s}{\partial r_s} \approx \frac{\partial u_m}{\partial r_m} \cos^2(\theta_m - \theta_s)$$

or: $$\frac{\partial u_s}{\partial r_s} \geq \frac{\partial u_m}{\partial r_m}$$

For large $r_m$

$$\frac{\partial u_m}{\partial r_m} + \frac{u_m}{r_m} = -\frac{\partial w}{\partial z} \approx \frac{\partial u_m}{\partial r_m} \leq \frac{\partial u_s}{\partial r_s}$$

This chart uses the same transformation equation as the previous chart but assumes that the measurements are made outside the microburst core. As the distance from the microburst core increases, simplifying assumptions can be made which result in an inequality relationship between the vertical wind gradient and the sensor measured radial wind.

NASA LaRC

## Vertical Shear Approximation

$$\frac{\partial u_s}{\partial r_s} \geq 0$$

**Assume inside microburst core:**

$$\frac{\partial w}{\partial z} = -2\frac{\partial u_s}{\partial r_s}$$

$$\frac{\partial u_s}{\partial r_s} < 0$$

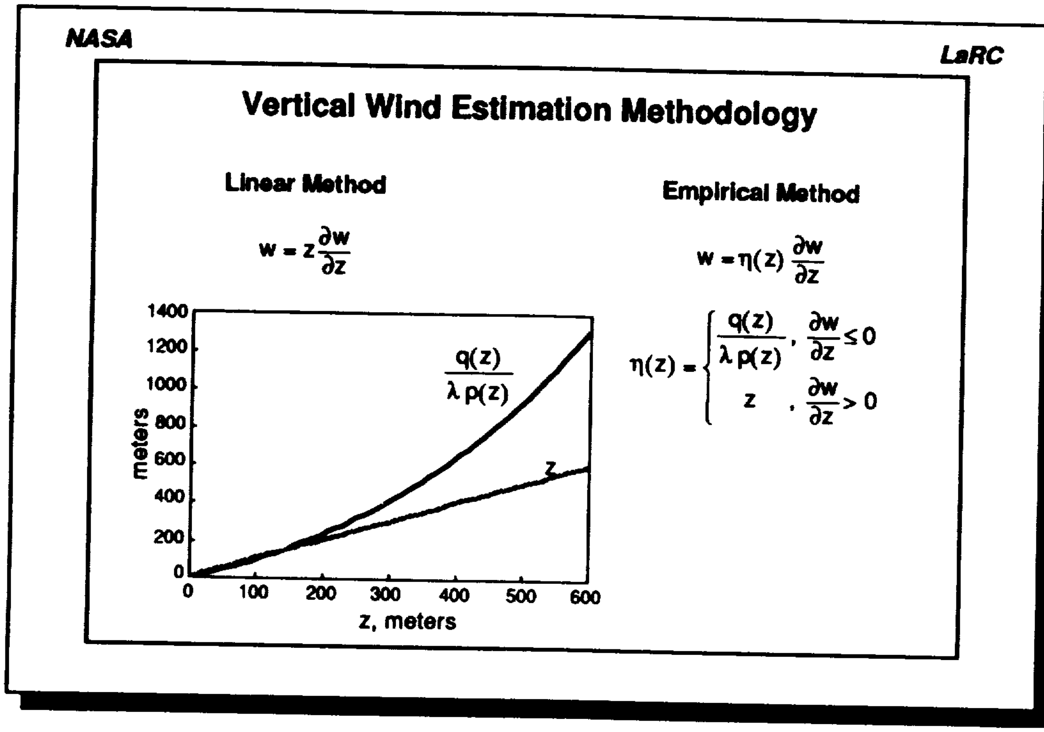
**Assume outside microburst core:**

$$\frac{\partial w}{\partial z} = -\frac{\partial u_s}{\partial r_s}$$

**or**

$$\frac{\partial w}{\partial z} = -\frac{1}{2}\left(3\frac{\partial u_s}{\partial r_s} + \left|\frac{\partial u_s}{\partial r_s}\right|\right)$$

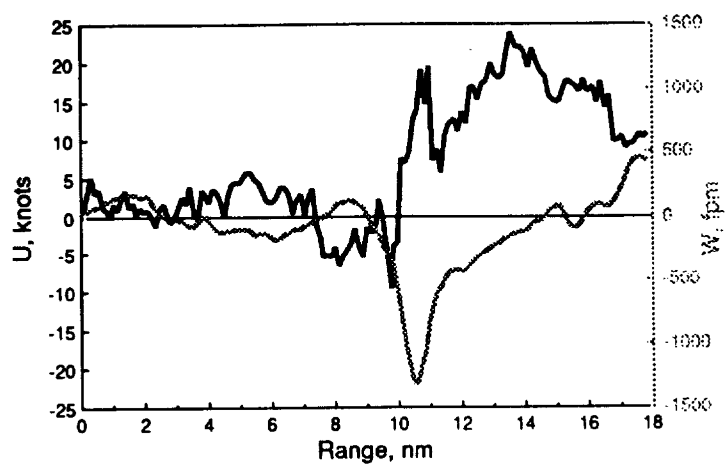
By combining the results of the previous two charts a simple approximation for the vertical wind gradient as a function of the sensor measured radial wind can be postulated.



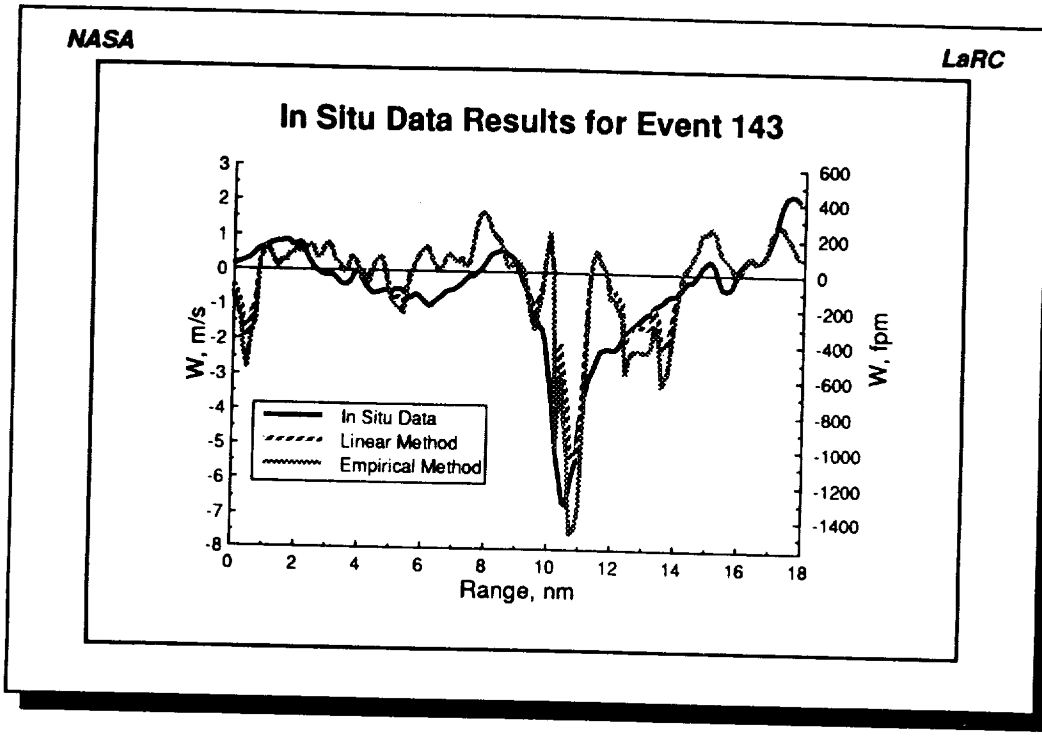

With an estimate of the vertical wind gradient in hand, the next step was to develop methodologies for computing the vertical wind from the vertical wind gradient. Two methodologies were developed. The simplest was the previously tested linear method. The other method was a derivation of the empirical model used in the initial study. The vertical shaping functions were used to define an altitude dependent function for computing the downdraft in the microburst core, and the linear method is used to compute the updrafts outside the microburst core.

NASA LaRC

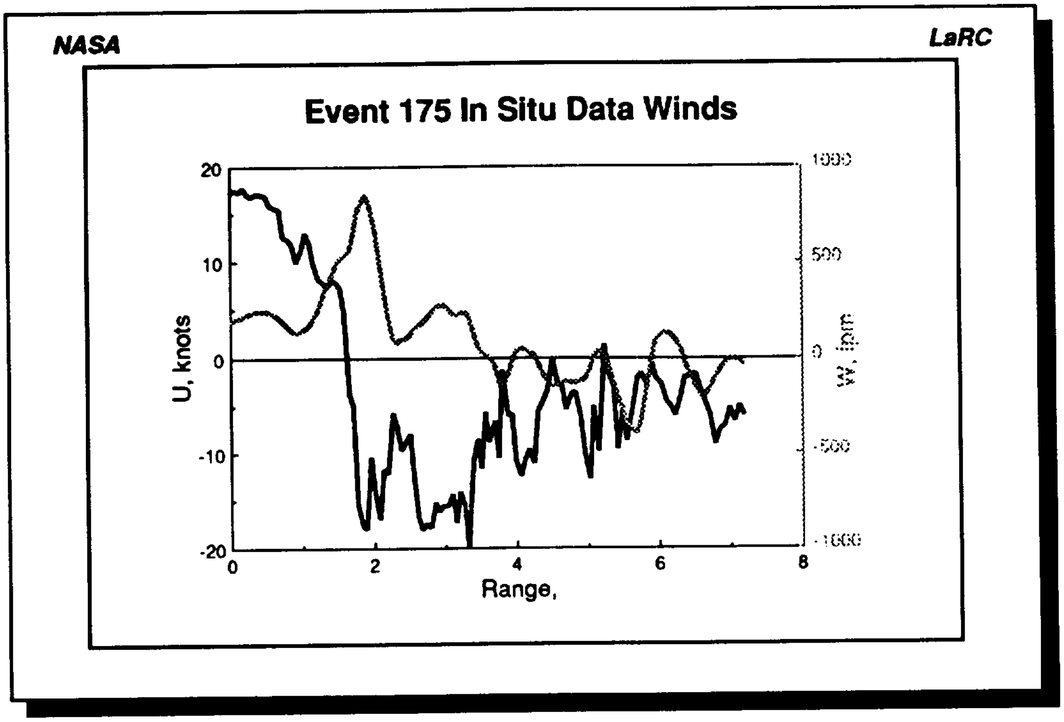
## Event 143 In Situ Data Winds



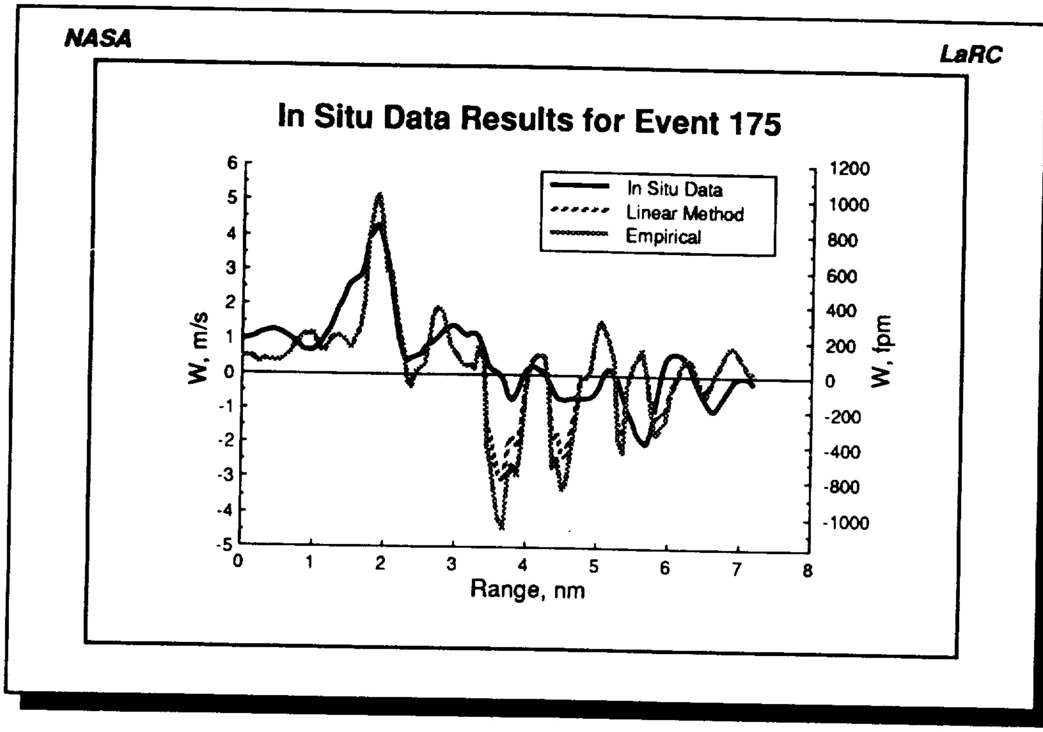

A quick test of the two new methodologies was conducted using the In Situ measured winds from microburst and gust front penetrations during the '91 flight tests. Presented on this chart are the horizontal (U) and vertical (W) wind measurements of microburst event 143. The horizontal wind was used as input into the vertical wind estimation methodologies. The measured vertical wind was used to compare with the esitmated value.




The vertical wind estimation results are shown on this chart for the new linear and empirical methods. As can be seen there is very little difference between the two methods for this particular case. The difference between the two methods only manifests itself at altitudes above 400 meters. This data was obtained at an altitude of about 300 meters. In general the vertical wind estimate follows the measured vertical wind profile. However, localized fluctuations in the horizontal wind profile resulted in spikes in the vertical wind estimation. This would indicate that the horizontal wind profile may need to be filtered to provide a smooth input for vertical wind estimation.




As mentioned earlier, the vertical estimation methods were also tested using gust front data. Presented on this chart are the horizontal and vertical wind measurements of gust front event 175.




Once again, the difference between the two methods is small at the altitude at which this data was collected. The methods estimated the updraft fairly well, but considerably over estimated two downdrafts. The current methodologies assume any divergence is a microburst and compute the downdraft accordingly. This can lead to the large downdraft estimates shown here. Some signal processing may be required to test the extent of the divergence and classify as a microburst or a local fluctuation accordingly.

NASA LaRC

## Results Summary

- Simple analytical models are sufficient for computing vertical winds at altitudes below 600 meters (~2000 ft).
- May need to tailor the vertical shear approximation to signature of radial shear measurement (how linear is the shear measurement over a given range?)
- Estimate of vertical wind is sensitive to "noise" in radial shear value

The preliminary data obtained to date would indicate that the simple analytical methods discussed here should be sufficient for estimating the vertical winds from horizontal wind measurements. However, there is still some signal processing research required to improve the vertical wind estimates and reduce the sensitivity to local fluctuations in the horizontal wind profile.

NASA

LaRC

## Future Activities

Focus:

- System implementation issues
  - Clutter
  - Resolution
- Signal processing?

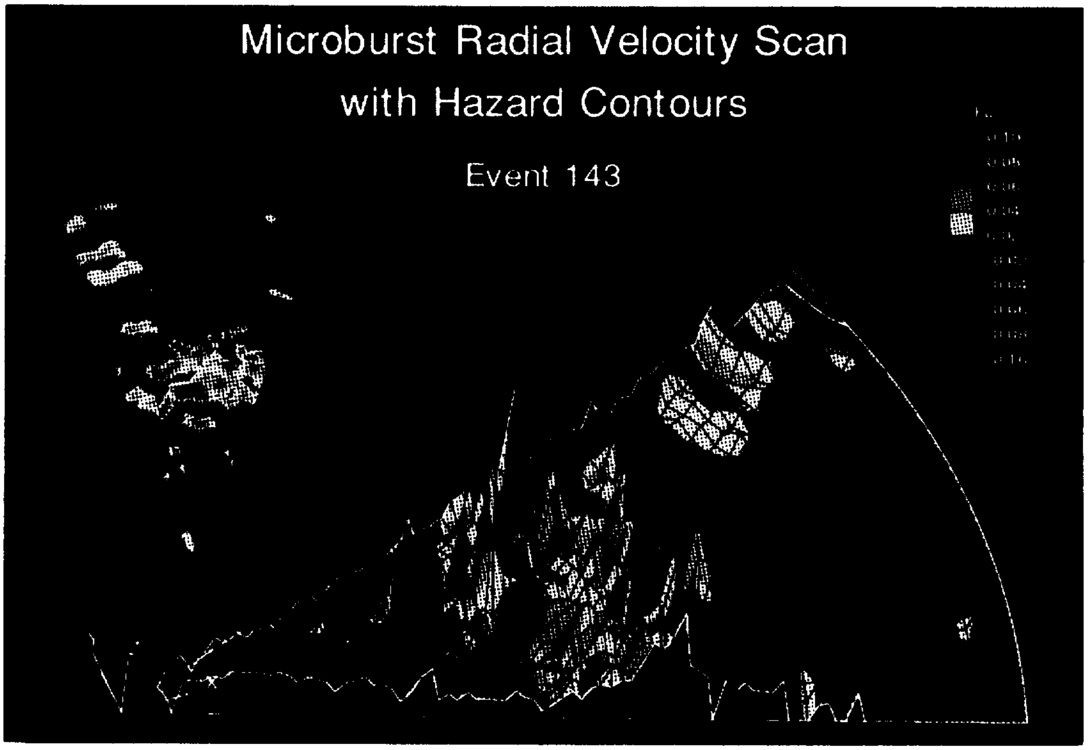
Approach:

- Use sensor simulations with high fidelity asymmetric microburst models
- Compare simulation results with flight test data

Future research efforts will focus on the system implementation issues for utilizing the two vertical wind estimation methodologies. The signal processing required to distinguish small scale vertical wind fluctuations from larger scale microbursts will be a large part of this research. The forward-look sensor characteristics, such as signal-to-noise ratio and range gate resolution, must be accounted for in the signal processing.

Sensor simulations with high fidelity asymmetric microburst models will be used to develop the signal processing. Once developed, the simulation results can be tested against flight test data to assess the "real world" performance.

ORIGINAL PAGE
COLOR PHOTOGRAPH




This last chart is used to illustrate the signal processing problem. Shown here is a surface plot of the horizontal wind measurement from a range/azimuth scan of an airborne Doppler radar. Included on the surface plot are the F-factor contours. Clearly, the signal processing will play an important role in hazard identification.

**Vertical Wind Estimation from Horizontal Wind Measurements**
Questions and Answers

**Q: Craig Wanke (MIT)** - I have a question about determining whether you are inside the core or outside the core. Do you need somehow to estimate in real time where the core of the microburst is or to know your distance from it somehow, to apply this?

**A: Dan Vicroy (NASA Langley)** - I probably wasn't very clear on that. Part of the problem with the model base approaches that I showed early on was that they were all referenced to the center of the microburst. Consequently, you did have to track the microburst and determine where the center of divergence was. We decided that was definitely not a good approach. The second methodology that I showed, which is the current implementation, just looks at the sign of the divergence, and if it is a positive divergence then you assume that you are in a microburst core and if it is a negative divergence then you are outside of the microburst core. That is probably too simplistic. Perhaps what you need to do is tailor the vertical shear approximation by doing a linearity check. If it is a positive divergence and that divergence is fairly linear over a given range, then perhaps you can assume that you are in a microburst core and then estimate the vertical wind accordingly. If it is not very linear over the appropriate range, then you can say that is just turbulence or a small downdraft and you would not want to treat it as a microburst.

**Q: Pat Adamson (Turbulence Prediction Systems)** - From the dual Doppler analysis, particularly in the Denver are, it was not uncommon to have 2:1 asymmetric events, as well as dry events with a low signal the noise. Have you done any error calculations on the estimation of vertical winds under those conditions?

**A: Dan Vicroy (NASA Langley)** - I haven't yet. That is part of that future work that we hope to wrap up by the end of the summer. The microburst simulations that I will be using from Fred will all be asymmetric, they will not be axisymmetric.

**Fred Proctor (NASA Langley)** - I have looked at a couple of very asymmetric events using this technique and it does surprisingly well.